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Annual Report

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Astrophysics Theory Program

On the Origin and Evolution of
Stellar Chromospheres, Coronae and Winds

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SUMMARY OF COMPLETED WORK

This grant was awarded by NASA to The University of Alabama in Huntsville (UAH) to construct state-of-the-art, theoretical, two-component, chromospheric models for single stars of different spectral types and different evolutionary status. In our proposal, we suggested to use these models to predict the level of the “basal flux,” the observed range of variation of chromospheric activity for a given spectral type, and the decrease of this activity with stellar age. In addition, for red giants and supergiants, we also proposed to construct self-consistent, purely theoretical, chromosphere-wind models, and investigate the origin of “dividing lines” in the H-R diagram. In the following, we list **six** specific goals for the **first** and **second** year of the proposed research and then describe the completed work.

- (1) To calculate the acoustic and magnetic wave energy fluxes for stars located in different regions of the H-R diagram.
- (2) To investigate the transfer of this non-radiative energy through stellar photospheres and to estimate the amount of energy that reaches the chromosphere.
- (3) To identify major sources of radiative losses in stellar chromospheres and calculate the amount of emitted energy.
- (4) To use (1) through (3) to construct purely theoretical, two-component, chromospheric models based on the local energy balance. The models will be constructed for stars of different spectral types and different evolutionary status.
- (5) To explain theoretically the “basal flux”, the location of stellar temperature minima and the observed range of chromospheric activity for stars of the same spectral type.
- (6) To construct self-consistent, time-dependent stellar wind models based on the momentum deposition by finite amplitude Alfvén waves.

First Goal:

The Lighthill-Stein theory for sound generation, recently modified by Musielak et al. (1994), has been used to calculate the acoustic wave energy fluxes for chromospherically active stars located in different regions of the H-R diagram. The obtained results (Ulmschneider, Theurer, & Musielak 1996) clearly showed that some previous calculations (Bohn 1984) were incorrect. The corrected acoustic wave energy fluxes have already been used by Buchholz, Ulmschneider, & Cuntz (1997) to predict theoretically the “basal heating” in late-type dwarfs and giants (see **Fifth Goal**).

We have also completed our analytical and numerical investigations of the generation of magnetic flux tube waves in stellar convection zones. Two papers describing the obtained analytical results will be submitted to *The Astrophysical Journal*. In the first paper (Musiak, Rosner, & Ulmschneider 1997a), we will describe our analytical theory of the generation of transverse tube waves. In the second paper (Musiak, Rosner, & Ulmschneider 1997b), we will present analytically calculated longitudinal and transverse wave energy fluxes for late-type dwarfs and giants; the fluxes for longitudinal tube waves will

be calculated by using a theory developed by Musielak, Rosner, & Ulmschneider (1989) and Musielak, Rosner, Gail, & Ulmschneider (1995). In addition, one paper (Ulmschneider & Musielak 1997) describing our numerical treatment of the generation of nonlinear longitudinal tube waves has been submitted to *Astronomy and Astrophysics*. The results of our numerical studies of the generation of transverse tube waves (Huang, Musielak, & Ulmschneider 1995) have already been published in the same journal. A paper presenting both longitudinal and transverse nonlinear wave energy fluxes for stars located in different regions of the H-R diagram (Musiak & Ulmschneider 1997) will also be submitted to the same journal. This will complete the first goal of the proposed research.

Second Goal:

We have investigated some aspects of propagation of adiabatic and nonadiabatic acoustic waves in the solar atmosphere and modeled chromospheric velocity fields in supergiants. The first project (Theurer, Ulmschneider, & Cuntz 1996; Sutmann, Musielak, & Ulmschneider 1997) is an expansion of earlier work by Sutmann & Ulmschneider (1995a,b) who studied the excitation of free and forced atmospheric oscillations by propagating acoustic waves and acoustic pulses. In the work by Theurer et al. (1996), radiative damping has been included. Radiative damping significantly modifies the acoustic wave propagation and, therefore, allows constructing more realistic chromospheric models, determined by the balance of shock wave heating and radiative cooling. In the paper by Sutmann et al. (1997), a general analytical theory of the excitation of free atmospheric oscillations is presented and the obtained results are used to explain the observed oscillations in the solar chromosphere.

In a paper recently published in *Astronomy and Astrophysics*, Cuntz (1997), presents the results from recent ab-initio models for the formation and time-dependent behavior of outer atmospheric flows in α Ori (M2 Iab) are given. It is assumed that the atmospheric flows are produced by stochastic shock waves. The wave models show distinct episodes of momentum and energy deposition produced by strong shocks generated by merging of shocks in the stochastic wave field. Sub- and supersonic inflows and outflows are generated at different atmospheric heights as function of the wave parameters adopted. Most importantly, it is found that the flow velocities given by the models encompass the velocity range revealed by the Fe II emission line components given by recent GHRS data (Carpenter & Robinson 1997). This result is evidence that nonmagnetic wave modes are relevant for the heating and dynamics of the outer atmosphere of α Ori and possibly other M-type supergiants as well.

In addition, we have investigated the efficiency of the energy transfer along magnetic structures. The results of this investigation have been published in *Physics of Plasmas* (see Huang 1996). Applications of these results to the solar and stellar atmospheres will be submitted for publication in *Astronomy and Astrophysics* (Huang, Musielak & Ulmschneider 1997a,b). The primary goal of this study is to investigate the validity of the thin flux tube approximation used in our chromospheric modelling. The relevant work was also done by Krogulec & Musielak (1997) and Ong, Musielak, Rosner, Suess, & Sulkanen (1997) who investigated the behavior of linear and nonlinear Alfvén waves in solar coronal holes and stellar atmospheres, and constructed first self-consistent and time-dependent

wind models (see **Sixth Goal** for details). Finally, we have also studied the propagation of longitudinal tube waves in atmospheres of K2 V stars and used the obtained results to construct first purely theoretical chromospheric models for these stars (see **Fourth Goal** for details). Similar studies will be done for transverse tube waves and this will complete the second goal of the proposed research.

Third goal:

We have addressed this goal by developing a new numerical code that implements a fully consistent solution of the time-dependent statistical rate equations for hydrogen and the thermodynamic and hydrodynamic equations for 1-D flows by using the method of characteristics (Cuntz & Höflich 1997). For each bound level of hydrogen considered one additional compatibility relation needs to be solved along the C^0 characteristic. The consistent solution of the time-dependent statistical rate equations together with the hydrodynamics equations is especially important in cases where the time-scales for hydrogen ionization and recombination are expected to be comparable to or larger than the time-scale for changes of the relevant hydrodynamic quantities. The existence of this behavior has been verified in the case of the solar chromosphere and transition layer, as discussed by Carlsson & Stein (1991, 1992, 1995) and Hansteen (1993), respectively. Carlsson & Stein found that in LTE almost all the energy dissipated by the shocks goes into ionization, so the temperature rise behind the shocks remains very small. In (time-dependent) non-LTE, however, the finite transition rates delay the ionization. As a consequence, the dissipated energy goes into thermal energy in the post-shock regions rather than ionization, leading to higher temperature amplitudes. In the work of Cuntz & Höflich (1997), test calculations have been made for the chromosphere of α Ori (M2 Iab) - see previous models by Cuntz (1992, 1997) by simulating the propagation of a strong shock formed as a consequence of an overshooting bubble. Cuntz & Höflich found that similar to the case of the Sun, the temperature jump of the shocks is *largely increased*, when non-instantaneous ionization of hydrogen is included. This behavior prevails in all calculation, independent whether radiative damping is included or not.

We believe that the new code developed by Cuntz & Höflich will be the cornerstone of many *ab-initio* chromosphere and wind models to be constructed because of its applicability to calculate radiative losses in stellar chromospheres.

Fourth Goal:

We have made a significant progress toward the main goal of the proposed research, which is to construct first purely theoretical, self-consistent and time-dependent stellar chromospheric models, by constructing such models for K2 V stars. The first results (Cuntz, Ulmschneider & Musielak 1997) have been submitted for publication in *The Astrophysical Journal Letters*. In this paper, we present self-consistent and time-dependent MHD models for chromospheres of stars with different levels of magnetic activity. Based on observational evidence, it is assumed that stars with faster rotation rate higher photospheric and chromospheric filling factors, which determine the shape of the tube (particularly the tube opening radius), the number of tubes on the stellar surface as well as the propagation and dissipation of the magnetic energy carried by longitudinal tube waves. The initial wave

energy fluxes have been supplied for these calculations by our theory of the generation of longitudinal tube waves described in **First Goal**. The filling factors used are estimated from a relationship between the photospheric magnetic field strength multiplied by the filling factor $B_0 f_0$ and the stellar rotation period P_{rot} . This relationship has been newly calculated by taking into account very recent magnetic field measurements by Valenti et al. (1995) and Rüedi et al. (1997), which are thought to be more accurate than earlier observational results.

The wave calculations by Cuntz, Ulmschneider, & Musielak (1997) are based on the treatment of nonlinear, radiatively-damped longitudinal flux tube waves, which have previously been considered for MHD heating models of the Sun (Herbold et al. 1985; Rammacher & Ulmschneider 1989; Ulmschneider, Zähringer, & Musielak 1991). The magnetic field strength B_0 inside the tubes at the photospheric level $\tau_{5000} = 1$ are calculated assuming approximate equipartition between the external gas pressure and magnetic pressure (e.g., Solanki 1996, Hasan & van Ballegoijen 1997). Compared to earlier work, we also consider various technical improvements in the wave code, including (1) the treatment of Mg II and Ca II emission lines (Ulmschneider, Muchmore, & Kalkofen 1987), (2) the consideration of NLTE ionization for the included sources of chromospheric radiative losses (Rammacher & Cuntz 1991), and (3) the use of the revised operator splitting method for the Mg II k and Ca II K emission by Buchholz et al. (1994) with proper inclusion of the shocks.

In the context of the proposed research, we calculated chromospheric models for K2 V stars with rotational periods between 5 and 40 days. We find that in tube models of fast rotating stars, the shock formation occurs closer to the photosphere if compared to stars of slower rotation. This effect should in principle enable the wave energy flux to reach greater atmospheric heights. Nevertheless, with respect to the general properties of the models, another effect is found to be much more important. That effect is the wider spreading of tubes (i.e., greater tube opening radius) in stars of reduced rotation. Due to this property, the wave energy flux is distributed over a cross section area considerably increasing with height, which decreases the waves amplitudes, the shock strengths, the energy dissipation rates of the waves, and the net radiative cooling rates. This latter effect is substantially magnified as in stars of slower (faster) rotation, the number of tubes on the stellar surface is significantly reduced (increased). Furthermore, due to the larger spreading of tubes in slow rotating stars, there are considerable large voids between the tubes, which do not substantially contribute to the overall chromospheric emission.

The results obtained by Cuntz, Ulmschneider, & Musielak (1997) should be regarded as the first step toward a consistent theoretical description of chromospheric emission in stars of different spectral types and evolutionary status, allowing us to derive theoretical chromospheric emission — stellar rotation relationships which can thus be compared with observations. The ultimate puzzle to resolve is a self-consistent model for the change of chromospheric emission losses with stellar evolution. Observational results demonstrating the decrease of chromospheric and transition layer emission with decreasing stellar rotation have been found both in main-sequence stars (Rutten 1986, 1987; Schrijver 1987) and (sub-)giants (Rutten 1987; Rutten & Pylyser 1988; Simon & Drake 1989); see also recent review by Jordan (1997). Our next step will be to calculate chromospheric emission losses for the stellar models we now have. Preliminary results for the case of the Sun using a multi-ray

radiative transfer method for simulating Mg II k and Ca II K line emission for arrays of flux tubes have already been obtained by Rammacher & Ulmschneider (1989). They carefully evaluated the role of the selected wave parameters, the geometrical flux tube parameters as well as the magnetic filling factors in the emergent Mg II and Ca II emission fluxes. These results need now to be updated and applied to other types of stars considering the most recent PRD radiative transfer methods by Ulmschneider (1994) and Hünérth & Ulmschneider (1995). We will be working on these projects in the third year of this funding.

Fifth Goal:

The constructed theoretical models of stellar chromospheres have to be tested against observational data. One of the most important tests is to account for the observationally established “basal flux”. We have already performed these calculations and the obtained results (see Buchholz, Ulmschneider, & Cuntz 1997) are accepted for publication in *The Astrophysical Journal*. In this paper we show that the chromospheric basal flux line can be obtained purely theoretically for a broad range of main-sequence stars (i.e., between spectral type F0 V and M0 V) and for two giants of spectral type K0 III and K5 III. This purely theoretical prediction is based the acoustic heating model and the corrected acoustic wave energy fluxes (see **First Goal**) have been used in these computations. It is found that the emergent radiation in Mg II $h+k$ and Ca II H+K agrees with the observational data given by Schrijver (1987), Rutten et al. (1991) and Judge & Stencel (1991) within a factor of 2. This agreement holds over nearly two orders of magnitude in chromospheric emission losses. In addition, the paper addresses several issues relevant to the proposed research, namely, location of the temperature minimum in stars of different spectral types and gravity, the role of acoustic waves in the photospheric temperature depression, changes in the local chromospheric cooling rates with stellar effective temperature, conversion of mechanical energy into radiative flux emission, and the relationship between the time-dependent chromospheric emission and the structure of the mean atmosphere. The obtained results also confirm the validity of the so-called Ayres’ scaling law (see Ayres 1979), which provides a relationship between the mass column density at the temperature minimum region of the stars and the stellar parameters, including the activity parameter for the chromospheric flux emission. This scaling is *independent* of the supposed chromospheric heating mechanism and thus provides an important independent test for our acoustic heating models.

The work of Buchholz, Ulmschneider, & Cuntz (1997) also points to limits in the theoretical method used, which need to be overcome in future calculations. Two points not yet included are of particular relevance: First, it would be important to also consider acoustic frequency spectra (e.g., Sutmann & Ulmschneider 1995a,b; Theurer, Ulmschneider, & Cuntz 1997), as they are expected to modify the hydrodynamic structure of the atmospheres as well as the generation of chromospheric emission losses considerably. Second, it would also be important to properly include effects of non-instantaneous ionization of hydrogen into the models as they critically affect both the temperature jumps of the shocks and the emerging line emission. This behavior has already been verified for the Sun some time ago (Carlsson & Stein 1991, 1992, 1995) (and by implication in similar types of stars)

and has now also been found in low-gravity stars as e.g. cool (super-)giants (Cuntz & Höflich 1997).

The results obtained by Buchholz, Ulmschneider, & Cuntz (1997) are important as they show that the chromospheric heating by acoustic waves is sufficient to sustain the observed basal flux. In the third year of this project, we will construct more chromospheric models that are based on magnetic heating (see **Fourth Goal**) and use them to account for the observed range of chromospheric activity for stars of the same spectral type.

Sixth Goal:

To address this goal, we have constructed first purely theoretical, time-dependent and self-consistent wind models based on the momentum deposition by nonlinear Alfvén waves. The full set of single-fluid magnetohydrodynamic (MHD) equations with the background flow is solved by using a modified version of the ZEUS MHD code (see Ong, Musielak, Rosner, Suess, & Sulkanen 1997). The constructed wind models are radially symmetric with the magnetic field decreasing radially and the initial outflow is described by the standard Parker wind solution. Our study focuses on the effects of Alfvén waves on the outflow. In contrast to previous studies, no assumptions regarding wave linearity, wave damping, and wave-flow interaction are made; the models thus naturally account for the backreaction of the wind on the waves, as well as for the nonlinear interaction between different types of MHD waves. So far, we have constructed models for outflows from solar coronal holes (see Ong et al.). The obtained results clearly demonstrate that the momentum deposition by Alfvén waves in the solar wind can be sufficient to explain the origin of fast stream components of the solar wind. The range of wave amplitudes required to obtain the desired result seems to be in good agreement with recent observations.

After obtaining these encouraging results, we have intended to use the developed code to construct self-consistent models of cool massive winds observed from late-type giants and supergiants. Unfortunately, Mr. Ong, who had been working on this project for the last two years and the project was supposed to be the main topic of his Ph.D. dissertation, decided to accept a position in the computer industry and discontinued working on his dissertation. As a result, we are currently rearranging our plans to accommodate this important part of our work.

The results described above have been obtained by the P.I. (Dr. Z. E. Musielak), Co-I's (Drs. R. Rosner and P. Ulmschneider), one senior research associate (Dr. M. Cuntz, who joined UAH in Jan. 1996), one junior research associate (Dr. P. Huang joined UAH in Jan. 1996 and left in May 1996 to work for industry), and one graduate student in physics (Mr. K. K. Ong, who recently left UAH to work for industry without completing his Ph.D.). Dr. Cuntz has devoted all his time to work on the project. He has been closely working with the P.I. and Dr. Ulmschneider, and with Mr. Ong while he was at UAH. He also worked with Dr. Huang during her stay at UAH. Dr. Rosner visited UAH in February 1996 and in April 1997 working on the wind acceleration problem. Dr. Ulmschneider visited UAH in Sept./October 1996 and in February 1997 working on the wave generation and propagation problem. In Fall of 1996, Mr. Ong spent three months at the University of Chicago working with Dr. Rosner on construction of self-consistent and time-dependent

stellar wind models. Finally, the P.I. has been working on several problems directly related to the project during the regular academic year when his salary is fully paid by UAH. For the academic year 1997/98, the P.I. has been granted a sabbatical leave from UAH. He will devote a significant portion of his time to work on research problems relevant to this project. This will be done without any additional charges to the grant.

As a result of this NASA support, we have completed 18 main and 7 contributed papers.

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- “On the Efficiency of Energy Transfer by Nonlinear Magnetohydrodynamic Waves Propagating Along Magnetic Slabs Structured Regions of the Solar Atmosphere” Huang, P., *Phys. Plasmas*, 3, 2579-2588 (1996).
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- “MHD Wave Energy Fluxes for Late-Type Stars” Musielak, Z. E., and Ulmschneider, P., *Astron. Astrophys.*, to be submitted (1998)
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